

I ZW 18 – A NEW WOLF-RAYET GALAXY¹

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ABSTRACT

We report the discovery of broad Wolf-Rayet emission lines in the *Multiple Mirror Telescope (MMT)* spectrum of the NW component of I Zw 18, the lowest-metallicity blue compact dwarf (BCD) galaxy known. Two broad WR bumps at the wavelengths $\lambda 4650$ and $\lambda 5800$ are detected indicating the presence of WN and WC stars. The total numbers of WN and WC stars inferred from the luminosities of the broad He II $\lambda 4686$ and C IV $\lambda 5808$ lines are equal to 17 ± 4 and 5 ± 2 , respectively. The WR-to-O stars number ratio is equal to ~ 0.02 , in satisfactory agreement with the value predicted by massive stellar evolution models with enhanced mass loss rates. The WC stars in the NW component of I Zw 18 can be responsible for the presence of the nebular He II $\lambda 4686$ emission line, however the observed intensity of this line is several times larger than model predictions and other sources of ionizing radiation at wavelengths shorter than 228\AA are necessary.

¹Spectroscopic observations presented herein were obtained with the Multiple Mirror Telescope, a facility operated jointly by the Smithsonian Institution and the University of Arizona.

²Visiting astronomer, Kitt Peak National Observatory, National Optical Astronomy Observatories, operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

Subject headings: galaxies: stellar content — galaxies: irregular — galaxies: ISM — H II regions — stars: Wolf-Rayet

1. INTRODUCTION

The presence of large numbers of Wolf-Rayet (WR) stars in star-forming galaxies is well established (Allen, Wright & Goss 1976; D’Odorico & Rosa 1981; Osterbrock & Cohen 1982; D’Odorico, Rosa & Wampler 1983; Hutsemekers & Surdej 1984; Kunth & Joubert 1985; Kunth & Schild 1986; Sargent & Filippenko 1991; Conti 1991; Vacca & Conti 1992). These galaxies are often called WR-galaxies and they are of quite heterogeneous types. We focus here on the problem of detection of WR stars in the low-mass and low-metallicity blue compact dwarf (BCD) galaxies. Systematic spectroscopic studies of BCDs have shown that in the spectra of $\sim 1/3$ of BCDs, broad WR bumps characteristic of late WN stars are present, mainly at $\lambda 4650$ (Izotov, Thuan & Lipovetsky 1994, 1997; Izotov & Thuan 1997a). The intensity of these bumps decreases with decreasing metallicity, in agreement with predictions of massive star evolution models and models of evolutionary population synthesis for star-forming regions (Maeder & Meynet 1994; Cerviño & Mas-Hesse 1994; Leitherer & Heckman 1995; Meynet 1995; Schaerer 1996). The lowest metallicity BCD in which WR stars have been detected has $\sim Z_{\odot}/10$, although BCDs can be as metal-deficient as $Z_{\odot}/50$. Are WR stars present in these extremely metal-deficient BCDs? In principle, massive stellar evolution theory (e.g. Maeder & Meynet 1994) does predict the evolution of the most massive low-metallicity stars through the WR stage. However, since the efficiency of mass loss by stellar wind decreases with decreasing metallicity, the total number of WR stars and the total duration of the WR phase in a star formation episode are significantly reduced at low metallicities. This trend led Schaerer et al. (1997) to conclude that in some metal-deficient BCDs, weak WR spectral features are not detected simply because of inadequate signal-to-noise ratio.

Several recent observations of low-metallicity BCDs have suggested that massive stars with mass loss are indeed present in galaxies with heavy element abundances less than $Z_{\odot}/20$. Imagery of I Zw 18 with *HST* by Hunter & Thronson (1995) has resolved its NW and SE components into stars, with the brightest star having $V \sim 22$ mag. Those authors attempted to find WR stars using a narrow-band image in the He II $\lambda 4686$ line and detected only two marginal WR candidates. They expected a large population of WR stars, given the presence of a large number of

red supergiants, so concluded that I Zw 18 is not a BCD with many Wolf-Rayet stars. Recently, Izotov & Thuan (1997b), from 4m Kitt Peak Mayall telescope spectrophotometry of I Zw 18, noted that WC stars are possibly present in the NW component. Finally, Thuan & Izotov (1997) have found evidence for stars with mass loss through the presence of P Cygni profiles in the *UV HST* spectra of two other very metal-deficient galaxies, SBS 0335–052 ($Z_{\odot}/40$) and Tol 1214–277 ($Z_{\odot}/23$). In this paper we continue our search for stellar populations with mass loss in very metal-deficient BCDs. We present high signal-to-noise ratio optical spectrophotometry of I Zw 18. We show that WR stars of different types are clearly present in this galaxy.

I Zw 18 is a BCD undergoing an intense burst of star formation. It was first recognized to have an exceptionally low metal abundance by Searle & Sargent (1972). Later studies by Lequeux et al. (1979), French (1980), Kinman & Davidson (1981), Pagel et al. (1992), Skillman & Kennicutt (1993), Martin (1996), Izotov, Thuan & Lipovetsky (1997) and Izotov & Thuan (1997b) have confirmed the oxygen abundance to be only $\sim 1/50$ of the solar value. Zwicky (1966) described I Zw 18 as a double system of compact galaxies, which are in fact two bright centers of star formation separated by an angular distance of $5''.8$. These two star-forming regions will be referred to subsequently as the brighter NW and fainter SE components. Later studies (Davidson, Kinman & Friedman 1989; Dufour & Hester 1990) have revealed a more complex structure with several additional diffuse features. However the NW and SE components dominate in brightness and this paper will focus on them. We describe the observations and data reduction in §2. In §3 we discuss the properties of WR stars in the BCD. We summarize our findings in §4.

2. OBSERVATIONS AND DATA REDUCTION

Spectrophotometric observations of I Zw 18 were obtained with the *Multiple Mirror Telescope (MMT)* on the nights of 1997 April 29 and 30. Observations were made with the blue channel of the *MMT* spectrograph using a highly optimized Loral 3073 \times 1024 CCD detector. A $1''.5 \times 180''$ slit was used along with a 300 groove mm^{-1} grating in first order and an L-38 second-order blocking filter. This yields a spatial scale along the slit of $0''.3 \text{ pixel}^{-1}$, a scale perpendicu-

lar to the slit of 1.9\AA pixel^{-1} , a spectral range of $3600 - 7500\text{\AA}$, and a spectral resolution of $\sim 7\text{\AA}$ (FWHM). For these observations, CCD rows were binned by a factor of 2, yielding a final sampling of $0''.6\text{ pixel}^{-1}$. The observations cover the full spectral range in a single frame that contains all the lines of interest and have sufficient spectral resolution to distinguish between narrow nebular and broad WR emission lines. The total exposure time was 180 minutes and was broken up into six sub-exposures, 30 minutes each. All exposures were taken at small air masses ($1.1 - 1.2$), so no correction was made for atmospheric dispersion. The seeing was $0''.7$ FWHM. The slit was oriented in the direction with position angle P.A. = -41° to permit observations of both NW and SE components. The spectrophotometric standard stars EG 247 and HZ 44 were observed for flux calibration. Spectra of He-Ne-Ar comparison lamps were obtained after each subexposure to provide flux calibration.

The two-dimensional spectra were bias subtracted and flat-field corrected using the IRAF³. For the NW component, the extracted one-dimensional spectra cover the brightest part of the galaxy with a spatial size of $\sim 5''$. Similar procedures were used for the SE component, resulting in one-dimensional spectra covering a region $5''$ wide at a distance of $5''.8$ from the NW component. The extracted spectra from each frame were then coadded and calibrated to absolute fluxes.

The observed line intensities have been corrected for interstellar extinction using the reddening law by Whitford (1958). Hydrogen lines have been also corrected for underlying stellar absorption, with the equivalent width for hydrogen absorption lines derived self-consistently together with the extinction coefficient from the observed intensities of all hydrogen lines. We show the observed $F(\lambda)/F(\text{H}\beta)$ and extinction and absorption-corrected $I(\lambda)/I(\text{H}\beta)$ line intensities for the NW and SE components in Table 1, along with the extinction coefficient ($C'(\text{H}\beta)$) and the equivalent width of the hydrogen absorption lines, the observed flux and equivalent width of the $\text{H}\beta$ emission line. The uncertainties for the tabulated relative line intensities are $\sim 0.5\%$ for the strongest lines and $\sim 10 - 15\%$ for the weakest lines.

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3. WOLF-RAYET STARS IN I ZW 18

In Figure 1 we show the spectra of the NW and the SE components of I Zw 18. The WR broad lines and strong narrow He II $\lambda 4686$ emission line are clearly present in the spectrum of the NW component. Thus, I Zw 18 is the lowest metallicity galaxy where WR stars are detected. In contrast, in the spectrum of the SE component WR emission lines are not convincingly detected. The weak emission seen at the wavelength $\sim 4700\text{\AA}$ is nebular emission from the [Fe III] $\lambda 4658$, He II $\lambda 4686$ and [Ar IV] $\lambda\lambda 4711, 4740$ lines. The appearance of a broad underlying emission feature here most probably arises from the blending of the wings of the individual nebular line profiles, but a very small contribution from WR stars cannot be excluded. The detection of the C IV $\lambda 5808$ broad line in the NW component suggests the presence of early WC stars, while the other broad lines are, most likely, evidence of early and late WN stars. The formation of C IV $\lambda 5808$ by WN stars can be ruled out because of its large FWHM ($\sim 80\text{\AA}$) which corresponds to early type WC stars (Smith, Shara & Moffat 1990). The approximate number of O and WR stars in the NW component can be estimated as follows. The observed fluxes of the C IV $\lambda 5808$ and broad He II $\lambda 4686$ emission lines are 8.3×10^{-16} and $1.49 \times 10^{-15}\text{ erg s}^{-1}\text{cm}^{-2}$, and that of $\text{H}\beta$ $\lambda 4861$ integrated along the slit is $4.93 \times 10^{-14}\text{ erg s}^{-1}\text{cm}^{-2}$. Correcting for interstellar extinction $C(\text{H}\beta) = 0.13$ dex for the NW component and adopting a distance $D = 10.8\text{ Mpc}$ (for the redshift $z=0.00274$ of the NW component with $H_0 = 75\text{ km s}^{-1}\text{ Mpc}^{-1}$), we derive the following luminosities: $L(\text{C IV } \lambda 5808) = 1.27 \times 10^{37}\text{ erg s}^{-1}$, $L(\text{He II } \lambda 4686) = 2.84 \times 10^{37}\text{ erg s}^{-1}$ and $L(\text{H}\beta) = 9.26 \times 10^{38}\text{ erg s}^{-1}$. Assuming that only $1/2$ of the light in $\text{H}\beta$ is contained within the slit width of $1''.5$, we derive finally $L(\text{H}\beta) = 1.85 \times 10^{39}\text{ erg s}^{-1}$. This value agrees well with that derived by Hunter & Thronson (1995) from the *HST* $\text{H}\alpha$ image. Adopting a value of $Q_0 = 49.05$ (Vacca & Conti 1992) for the logarithm of the number of Lyman continuum photons emitted per second by an O7V star and assuming Case B recombination and an instantaneous burst of star formation, we derive $N(\text{O7V}) = 381$. To derive the total number of O stars, we need to take into account the age of the stellar population and the IMF slope. A measure of the age of the burst of star formation is the equivalent width of the $\text{H}\beta$ emission line. The low equivalent width of 56\AA in the NW component of I Zw 18 corresponds to an age of $4 - 5$

Myr, assuming a Salpeter IMF (Leitherer & Heckman 1995). This value is in good agreement with the results of direct *HST* photometry of the brightest stars by Hunter & Thronson (1995). They found stars as old as 5 Myr in the NW component. Then, the total number of O stars is ~ 3 times larger (Schaerer 1996) and is equal to ~ 1100 . This approximate value is in good agreement with the number of O stars of 1300 derived by Hunter & Thronson (1995) from the luminosity function.

The number of WR stars is estimated from the luminosity of the WR emission features. While the main contribution to the $\lambda 5808$ emission is from WC4 stars, the emission in the $\lambda 4650$ feature is produced by WR stars of different types. However, the observed flux ratio, $f(\lambda 4650)/f(\lambda 5808) \sim 3$, is significantly greater than that expected for WC4 stars (Smith, Shara, & Moffat 1990). Therefore, the dominant contributors to the broad He II $\lambda 4686$ emission are WNL stars. The moderate spectral resolution and line blending, however, prevent drawing more decisive conclusions about the origin of the $\lambda 4650$ bump. The derived number of WNL stars should therefore be considered as only indicative. Adopting the luminosity of a single WC4 star in the C IV $\lambda 5808$ line as equal to 2.5×10^{36} erg s $^{-1}$, and that of a single WNL star in He II $\lambda 4686$ as equal to 1.7×10^{36} erg s $^{-1}$ (Conti 1991; Vacca & Conti 1992), we derive the following numbers of stars: $N(\text{WC4}) = 5 \pm 2$, $N(\text{WNL}) = 17 \pm 4$. This gives $N(\text{WR})/N(\text{O}) = 0.02$ and $N(\text{WC})/N(\text{WN}) = 0.3$.

Meynet (1995) presented new evolutionary population synthesis models based on the most recent grids of stellar models computed at the Geneva Observatory. He studied the effects of changes in the rates of mass loss by stellar winds on the massive star populations born in a starburst. According to Maeder & Meynet (1994), the high mass loss rate stellar models are to be preferred over the standard ones on the basis of comparisons with the observed luminosities, chemical compositions and number statistics of WR stars in zones of constant star formation rate. In starburst galaxies, the presence of WC stars at very low metallicity is predicted only by models of massive star evolution with enhanced mass loss (Meynet 1995), while the models with standard mass loss rates derived by de Jager, Nieuwenhuijzen & van der Hucht (1988) and scaled with metallicity as $Z^{0.5}$ fail to produce WC stars at the metallicity of I Zw 18. Therefore, the detection of WC stars in I Zw 18 gives strong sup-

port to the idea of enhanced mass loss in massive low metallicity stars. Furthermore, we find satisfactory agreement between the observed and theoretical WR/O and WC/WN ratios at the metallicity of I Zw 18. Meynet (1995) has calculated evolutionary population synthesis models only for metallicities as low as $Z_{\odot}/20$. At this metallicity, assuming an instantaneous burst of star formation and an IMF $dN/dM \propto M^{-2}$ for the massive stars, his models predict $\text{WR}/\text{O} \approx 0.035$ and $\text{WC}/\text{WN} \approx 0.5$ for peak values. Scaling these values as $Z^{0.5}$ to the I Zw 18 heavy element abundance $Z_{\odot}/50$ gives WR/O and WC/WN ratios close to those derived from the observations.

The detection of WC stars in I Zw 18 can help resolve the long-standing problem of the origin of the strong nebular He II $\lambda 4686$ line in the NW component, which is several orders of magnitude greater than predicted by photoionized H II region models. Schaerer (1996) has shown that WC stars can significantly increase the ionizing flux shortward of 228\AA , thus leading to the formation of a He^{++} zone in the H II region and increasing the recombination He II $\lambda 4686$ emission line luminosity by several orders of magnitude. However, this model predicts the maximum value of the nebular He II $\lambda 4686$ emission line intensity to be only $\sim 1\% - 2\%$ that of $\text{H}\beta$ when the age of the star forming region is not greater than 3 Myr. The He II line intensity is expected to decrease from this maximum value for a somewhat older stellar population like the one in I Zw 18. This is in contrast to the observed intensity of the nebular He II $\lambda 4686$ emission line in the NW component of I Zw 18 which is 4% that of $\text{H}\beta$, larger than the predicted peak value. Furthermore, this model fails to explain the presence of strong He II $\lambda 4686$ in the galaxies where WC stars have not been detected (Izotov et al. 1997). We conclude therefore that, in addition to WC stars, some other source of ionizing radiation at wavelengths shorter than 228\AA must be invoked.

4. CONCLUSIONS

We have obtained high signal-to-noise ratio spectrophotometric observations of I Zw 18, the most metal-deficient BCD known, in an attempt to detect the broad low-intensity emission lines of WR stars. We have obtained the following results:

1. Broad emission lines at wavelengths $\sim \lambda 4650$ and $\lambda 5800$ have been detected in the spectrum of the NW component of I Zw 18 implying the presence of

WN and WC stars, while in the younger SE component these lines are absent. Thus, I Zw 18 is the lowest-metallicity Wolf-Rayet galaxy known to-date.

2. The total numbers of WNL and WC4 stars in I Zw 18 are 17 ± 4 and 5 ± 2 respectively, and the total number of O stars is ~ 1100 . The existence of WC stars at the very low metallicity of $Z_{\odot}/50$ in I Zw 18 confirms predictions of massive stellar evolution models with enhanced mass loss rates (Meynet 1995), while the models with standard mass loss rates fail to explain the presence of WC stars in I Zw 18. The observed WR/O and WC/WN ratios of 0.02 and 0.3 respectively, are in satisfactory agreement with evolutionary population synthesis models based on stellar evolution models with enhanced mass loss and extrapolated to the metallicity of I Zw 18. Although the WC stars detected in I Zw 18 could be responsible for the presence of the strong nebular He II $\lambda 4686$ emission line, the observed value of the nebular He II $\lambda 4686$, 4% that of H β , is several times larger than theoretical predictions. We conclude that additional sources of ionizing radiation at wavelengths shorter than 228Å need to be present.

This international collaboration has been made possible by the support of INTAS research grant No 94-2285 and NATO collaborative research grant 921285. Y.I.I. is grateful for the hospitality of the National Optical Astronomy Observatories and the MMT Observatory. C.B.F. acknowledges the support of the NSF through grant AST 93-20715. We thank Phil Massey for useful discussions and the referee, Cesar Esteban, for thoughtful comments that improved the content and presentation.

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Fig. 1.— The spectra of the NW and the SE components in the BCD I Zw 18. The broad nitrogen and carbon lines in the spectrum of the NW component are marked indicating the presence of WN and WC stars. The permitted Mg I $\lambda 4571$ and narrow nebular He II $\lambda 4686$ emission lines are also marked. The broad WR emission lines are absent in the spectrum of the SE component where the nebular [Fe III] $\lambda 4658$, He II $\lambda 4686$ and [Ar IV] $\lambda\lambda 4711, 4740$ emission lines are marked. The spectra have been smoothed using a 3-point box-car.

TABLE 1
EMISSION LINE INTENSITIES

Ion	I Zw 18 (NW)		I Zw 18 (SE)	
	$F(\lambda)/F(\text{H}\beta)$	$I(\lambda)/I(\text{H}\beta)$	$F(\lambda)/F(\text{H}\beta)$	$I(\lambda)/I(\text{H}\beta)$
3727 [O II]	0.228	0.238	0.510	0.499
3868 [Ne III]	0.143	0.148	0.139	0.136
3889 He I + H8	0.102	0.195	0.155	0.200
3968 [Ne III] + H7	0.134	0.222	0.169	0.212
4101 H δ	0.196	0.276	0.232	0.270
4340 H γ	0.410	0.472	0.443	0.468
4363 [O III]	0.069	0.068	0.054	0.052
4471 He I	0.022	0.021	0.034	0.033
4686 He II (neb)	0.041	0.040	0.007	0.006
4686 He II (WR)	0.063	0.062
4861 H β	1.000	1.000	1.000	1.000
4959 [O III]	0.731	0.690	0.591	0.573
5007 [O III]	2.197	2.069	1.776	1.724
5808 C IV (WR)	0.035	0.031
5876 He I	0.074	0.066	0.095	0.092
6563 H α	3.163	2.743	2.834	2.745
6678 He I	0.030	0.026	0.028	0.027
6717 [S II]	0.024	0.021	0.043	0.042
6731 [S II]	0.019	0.016	0.031	0.030
7065 He I	0.026	0.022	0.024	0.024
7135 [Ar III]	0.019	0.016	0.019	0.018
$C(\text{H}\beta)$ dex	0.130		0.010	
$F(\text{H}\beta)^{\text{a}}$	2.36		1.76	
$EW(\text{H}\beta)$ Å	56		129	
$EW(\text{abs})$ Å	2.9		3.9	

^ain units of 10^{-14} ergs s $^{-1}$ cm $^{-2}$

